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Analysing the Co-Benefits of transport fleet and fuel policies in reducing $PM_{2.5}$ and CO_2 emissions

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ABSTRACT

Previous research has highlighted the dangers of considering air pollution policy and climate change policy separately. Measures to reduce CO_2 emissions have been adopted in several countries, and in some instances, these have resulted in increases in some air pollution emissions and vice versa. Research has also highlighted the potential co-benefits of air pollution and climate change mitigation policy where these are considered together. This paper addresses the co-benefits of climate change mitigation policies to reduce the air pollution ($PM_{2.5}$) and climate change (CO_2) impacts of passenger cars, using a scenario-based approach in Ireland. Scenario-based approaches have previously been adopted for these pollutants in several co-benefit studies. However, a detailed disaggregation of non-exhaust $PM_{2.5}$ by brake, tyre and road abrasion, and a disaggregation of both $PM_{2.5}$ and CO_2 by a number of current and future passenger car technologies have not been considered to date. The current study, therefore provides deeper insights into the impact of policy on exhaust and non-exhaust emissions. In order to derive detailed disaggregated emission, an add-on module was developed for a well-known emission modelling software (COPERT). The add-on module adopted concepts and parameters from previous research papers and analysis from the COPERT software to estimate fuel-based emissions e.g. exhaust and disaggregated non-exhaust $PM_{2.5}$ and CO_2 emissions. To analyse future scenarios (2015–2035), estimation was initially conducted using that software for the current Irish fleet data. This estimation was later replicated using the add-on module, as a baseline scenario considering a different disaggregation of the same passenger car fleet. Two additional estimations were conducted in the add-on module: An Electric Vehicle policy scenario, and a scenario to show the effects of a ban on the sale of conventional vehicles by 2030. The results revealed that CO_2 emissions continuously decreased in the projection period, however, reductions of $PM_{2.5}$ reversed from the year 2028 due to increases in the non-exhaust component of $PM_{2.5}$ emissions. Under the two alternative scenarios, a 52–69% reduction of CO_2 could be possible whereas only a 9–15% reduction in $PM_{2.5}$ could be achieved by 2035. In conclusion, non-exhaust $PM_{2.5}$ was found to have a larger share (as much as 34 times that of exhaust emissions) in 2035 where passenger cars with alternative technologies represented a major share in the fleet. The research also provided a methodology capable of detailing the CO_2 and $PM_{2.5}$ emissions in future scenarios for a range of vehicle technologies. This research also highlights an urgent need for investigation of emission factors for several emerging passenger car technologies.

1. Introduction

Previous investigations have highlighted the lack of integration of air pollution and climate change policy in the EU (Bollen and Brink, 2014). Several climate change policies have been shown to have negative impacts on air pollution and vice versa, and thus their integration is crucial to avoid unintended consequences. Air pollutant reductions may accelerate the increase in global mean temperature in the short term, however, eventually, these will contribute to long-term climate stabilization (IGES, 2010; Raes, 2009). In addition, reduction of air pollution will immediately improve the air quality and thus, will reduce negative consequences on population health. In Ireland, reduction of $PM_{2.5}$ concentrations is one of the key challenges identified by the Irish EPA (O'Dwyer, 2016) and the reduction of $PM_{2.5}$ is also a major challenge

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throughout most of Europe (Kiesewetter et al., 2015). However, $PM_{2.5}$ does not receive much attention in the policy arena for a quantitative reduction of mass in comparison to heavily regulated pollutants like CO_2. Rather, $PM_{2.5}$ is a policy concern from the perspective of air quality and health.

Particulate matter in vehicle exhaust has been declared as a probable carcinogen to humans (IARC, 1989) and also has been linked to various adverse health impacts (Lee et al., 2010; Hesterberg et al., 2009; Krivosbto et al., 2008; IARC, 1989). Fine particulates have been reported to be more toxic to humans than larger particles (Oberdörster et al., 2000; Oberdorster, 2000; Pope, 2000) and WHO states that both short and long-term exposures to $PM_{2.5}$ result in adverse health effect (WHO, 2013). $PM_{2.5}$ is becoming a cause for concern because of relatively short, but high exposures, to a major share of the population during their movements. The transport sector in Ireland contributed 11.7% of the total emissions of $PM_{2.5}$ in 2015, with more than 90% of this coming from road transport (EPA, 2016). An investigation in the road transport sector in 2014 found that Passenger Cars (PCs) contributed the largest proportion (56%) to $PM_{2.5}$ of all vehicle categories in 2013 (Alam et al., 2015). EPA (2016) reported in their latest estimation that the contribution of the PCs on road transport $PM_{2.5}$ were 56% in 2014 and 56.4% in 2015. Emissions of $PM_{2.5}$ from PCs were estimated to increase to a 63% share of total road transport emissions by 2035 (Alam et al., 2015). The projection was conducted using the COPERT model and the Irish national road transport emissions database in 2014. COPERT is widely used in the European Union to calculate real-world air pollutant and GHG emissions from road transport for existing and historic years (EEA, 2016) and many investigations also used the COPERT model or a modified COPERT methodology to estimate future emissions (Alam et al., 2017a; Vanhulsel et al., 2014). COPERT reports non-exhaust $PM_{2.5}$ emissions together, excluding emissions from road abrasion. However, a detailed distribution of $PM_{2.5}$ according to the brake, tyre wear, road abrasion and exhaust $PM_{2.5}$ emissions may be necessary to provide a better understanding of the extent of contributing sources for the future transport fleet. Such methodological improvement may also be needed to cover a number of modern vehicles, e.g. Fuel Cell Vehicle (FCV) which is not included in COPERT. The above methodological improvements will also affect the estimation of other pollutants like CO_2.

CO_2 is the primary Greenhouse gas (GHG) which is directly related to fuel consumption, unlike $PM_{2.5}$. Reduction of CO_2 is crucial in meeting the global 2 °C temperature stabilization targets. In Ireland, 18.7% of total CO_2 at national level originated from PCs in 2015 (EPA, 2016) and the policies that are currently in place and directly relevant to PCs are the bio-fuel policy and Electric vehicle (EV) policy (DCENR, 2016, 2014). This investigation addressed these policies and relevant policies that were currently under consideration in different EU countries to estimate the likely co-benefits in $PM_{2.5}$ reduction. A scenario-based approach is presented in this paper using an improved methodology to quantify $PM_{2.5}$ and CO_2 from PCs in Ireland. Similar scenario based co-benefits analysis was conducted in a number of recent investigations that accounted for both $PM_{2.5}$ and CO_2 (Dhar et al., 2017; Lott et al., 2017; Pathak and Shukla, 2016; Xia et al., 2015). Analysis using a scenario based approach is an efficient way of understanding the uncertain future to analyse the impact of changes in policies and measures. Several methodologies were applied in these studies to predict future emissions. Dhar et al. (2017) applied an energy system models to account co-benefits from the PC sector in India where disaggregated emissions for $PM_{2.5}$ was not emphasised. Lott et al. (2017) applied a bottom-up techno-economic energy systems model for all sectors and accounted for both exhaust and non-exhaust emission, however, a detailed segregation of the future vehicle class was not the prime focus of the study. Pathak and Shukla (2016) applied an energy-based model for all road transport, where exhaust and non-exhaust $PM_{2.5}$ emissions was not emphasised. Xia et al. (2015) estimated CO_2 and $PM_{2.5}$ in alternative scenarios, primarily based on the changes in vehicle kilometres travelled. A combination of models was applied in that study for all road transport that also included exhaust and non-exhaust emissions, however, a detailed segregation of vehicle class was not included. A detailed vehicle classification in emissions estimation was considered for quantifying CO_2 or GHG emissions in a number of studies (Alam et al., 2017a, 2017b; Zhang et al., 2016; Hao et al., 2015). In this paper, a detailed segregation of PC fleet based on the fuel and engine technology was applied following the authors' previous research (Alam et al., 2017a).

In order to model an uncertain future, the methodology developed in this study considers a wide range of PC technology for a detailed analysis of the disaggregated emission. This provides a scope for greater understanding of the impact of the different PC technologies in different exhaust and disaggregated non-exhaust emission. The scenarios analysed here are of a relevance to a number of existing policies, both nationally and internationally, such as the CAFE Directive (2008/50/EC), proposed targets in the EU National Emissions Ceiling (NEC) Directive (2001/81/EC), and the Gothenburg protocol.

2. Methodology

2.1. Methodological framework

The current national emissions projection system for road transport in Ireland is based on three fuel types: gasoline (fossil & biofuel), diesel (fossil & biofuel) and Liquefied Petroleum Gas (LPG) and corresponding three PC technologies, namely, gasoline, diesel, and LPG. However, the hybrid gasoline and Compressed Natural Gas (CNG) PC technologies were not included in the projection system (EPA, 2016). In order to produce a baseline scenario for this analysis a modification of the national emissions inventory model was developed in COPERT. Here, Hybrid Electric Vehicle (HEV) PCs powered by Gasoline were separated from the aggregated gasoline PCs in the national emissions inventory model following Alam et al. (2017a), as it was a considerable category in terms of its share in the fleet. This scenario was run with a similar mileage as gasoline PCs for HEV with an additional amount of bio-fuel (6.8% up to 1990 and then 12% until 2035) for all road transport vehicle categories (Alam et al., 2017a). Results from this COPERT scenario were only collected for PCs and labelled as the “COPERT Scenario”. This was then processed and entered into an add-on module to create a “Baseline Scenario” for this study. The COPERT Scenario has two functional roles in the methodology: firstly, to provide emission factors required to develop the model; secondly, the total time series emissions from COPERT for 2015 to 2035 becomes a benchmark to verify the projection made by the add-on module in the baseline scenario. Two different alternative scenarios (“EV Policy Scenario” and “Non-conventional PC Scenario”) were then run in the add-on module to compare against the Baseline Scenario. To develop a fleet composition for the alternative scenarios, a fleet scenario tool developed by Alam et al. (2017a) was also applied for the period 2015 to 2035. In the alternative scenarios, the addition of modern technologies to the fleet was taken into account.

An add-on module for COPERT was developed that provided emissions projections segregated according to exhaust, and non-exhaust emissions and its subdivisions. The add-on module estimated energy consumption for a wide range of PC categories using fuel efficacy uplift multipliers for alternative PC technologies e.g. FCV from a number of previous investigations (Gambhir et al., 2015;

Hill et al., 2012; Ou et al., 2010). The total emission in this study was calculated based on the estimated fuel demand (Gambhir et al., 2015; IPCC, 2006) as well as total mileage by the add-on module for exhaust and non-exhaust emissions (EMEP/EEA, 2016). Although the total mileage between COPERT outputs and the add-on module remained the same, the fuel demand varied due to changes in vehicle technologies in different scenarios. Implied emission factors from COPERT were included in the add-on module to facilitate $PM_{2.5}$ exhaust calculation, which was considered as fuel based. Emission factors for exhaust $PM_{2.5}$ was difficult to obtain as it was not directly related to fuel consumption, rather engine technology and exhaust system, e.g. particulate filters play a role in the amount of $PM_{2.5}$ emission exhausted (IEA, 2009). For $PM_{2.5}$ exhaust and different non-exhaust emission factors of new PC technologies, e.g. FCV that were not available as implied emission factors, these were directly obtained or estimated from a number of previous investigations (EMEP/EEA, 2016; Timmers and Achten, 2016; Ciborowski et al., 2007). Where implied emission factors for CO_2 were not available, e.g. CNG PCs, fuel demand was calculated based on the fuel efficacy and default emission factor based on the carbon concentration (IPCC, 2006). Like CO_2 and exhaust $PM_{2.5}$, non-exhaust emissions were segregated into brake, tyre and road abrasion, and varied according to the distribution of mileage in different vehicle technologies. Road abrasion $PM_{2.5}$ was not reported under COPERT and was calculated using EMEP/EEA recommended emissions factors (EMEP/EEA, 2016).

The data, however, could not directly be transferred from COPERT to the add-on module. Both fleet data and implied emission factors required pre-processing before feeding to the add-on module. The add-on module required vehicle information disaggregated between fuel technologies and at the level of newly registered and survived vehicles, according to their different years. Thus, the PC technologies at EURO standard were required to be aggregated at fuel technology level and disaggregated using the survival rate. EURO standard refers to the PC classification based on the emission limit complying with European emission regulation directives (Alam et al., 2017a,b). EURO standards applied in this study were presented in the Fig. I, Annex I.

The fleets for the Baseline Scenario and EV Policy Scenario were obtained from the author's previous study at this disaggregated level (Alam et al., 2017a). A similar estimation was conducted for the Non-conventional PC Scenario using a scenario development approach (Alam et al., 2017a). The add-on module takes a detailed breakdown of the fleet categories according to the major fuel types that are segregated into newly registered and survived vehicles. It then applies improvements in their fuel efficiency (where applicable) along with fuel based mileage distribution to calculate fuel demand for the same amount of mileage projected in an initial estimation by COPERT. It is capable of estimating both $PM_{2.5}$ and CO_2 emissions in accordance with the mileage efficiency improvements for different vehicle fuel technologies. The methodology of the study is presented in Fig. 1.

2.2. Add-on module

The add-on module was developed with gasoline, diesel, HEV (Gasoline & diesel), Plug-In Hybrid Vehicles (PHEV) for both Gasoline & diesel, EV, FCV, CNG and LPG PC categories. PHEV was assumed to be driven by electricity for 40% of its mileage (Ciborowski et al., 2007). The module applied two separated methodologies for exhaust and non-exhaust $PM_{2.5}$ and CO_2 emissions. For non-exhaust emissions, the add-on module calculated emissions from mileage, implied emissions factor (g/km) and PC population according to the category distribution. As implied emission factor was selected for exhaust emission, the fuel efficiency in the add-on module has not been considered in fuel demand estimation except in CO_2 estimation for CNG and LPG PC which applied carbon content based emission factors. The implied factors were both weighted by engine size and EURO technology with efficiency improvement. Although COPERT did not account for euro technology beyond EURO 6 (EMISIA, 2016), fuel efficiency at the add-on module could be applied to include the impact of beyond EURO 6 technology. Thus, the estimation based on implied emission factors has room for further improvement. Currently, the add-on module considered zero efficiency improvement in future years in fuel demand for estimating exhaust $PM_{2.5}$ (all categories) and CO_2 (all except CNG and LPG) emission to adjust with the efficiency weighted implied emission factors. The implied emission factors that were adopted from COPERT in the analysis were presented in Tables I–III in the Annex II. These were verified against NAEI (2013) fleet weighted emission factors for $PM_{2.5}$ and IPCC (2006) for CO_2. Along with population, mileage, and emission factors, other parameters required in the Add-on module included fuel efficiency, fuel efficiency improvement rate, fuel efficiency uplift multipliers, and the share of distance travelled using gasoline/diesel for PHEV. Details of these parameters are discussed in the relevant later sections. The add on module for the Baseline Scenario was added in the Annex III.

2.2.1. Emission factors

Non-exhaust emission factors (2015–2035) for brake wear, tyre wear and road abrasion were obtained from COPERT data. EV implied emission factors for non-exhaust were estimated from COPERT output and using the results of Timmers and Achten (2016). It was found that EV emission factors were 21.6% and 18.4% higher than conventional gasoline and diesel vehicles for tyre and road abrasion, because of vehicle weight. The brake wear emission factor was set to zero following Timmers and Achten (2016) who has considered this value as a conservative estimation. FCV emission factors were assumed to be similar to EV with the assumption of having a regenerative braking system. In reality, there may be lower emission factors for brake wear (Barlow, 2014) for these technologies which can easily be adopted by the model in future. All $PM_{2.5}$ emission factors for CNG were assumed similar to the LPG PC.

Similarly, exhaust $PM_{2.5}$ implied emission factors for gasoline, diesel and LPG were obtained from COPERT data processing, for the years 2015–2035. In comparison to the conventional PC, Ciborowski et al. (2007) estimated a 42.9% and 64.3% reduction in exhaust $PM_{2.5}$ emissions in HEV and PHEV (where PHEV was driven for 40% of its mileage by wind-generated electricity). This reduction rate was applied to the $PM_{2.5}$ implied emission factors of gasoline and diesel PCs to represent HEV (Gasoline and Diesel) and PHEV (Gasoline & diesel) in the current study. $PM_{2.5}$ exhaust implied emission factors and CO_2 for EV and FCV were set to zero. CO_2 implied emission factors for gasoline and diesel PCs were obtained from COPERT data.

In order to obtain implied emissions factors from COPERT, fuel adjusted mileage (km), exhaust PM (tonne), total $PM_{2.5}$ (tonne), total CO_2 emissions (tonne), fuel consumption (tonne) and PC fleet disaggregated by fuel and EURO emission technologies were estimated. Disaggregated fuel consumption was converted to the energy consumption using fuel to energy conversion factors and biofuel blends (Duffy et al., 2015). The fuel efficiency (MJ/km) was derived at the disaggregated level. An average fuel efficiency (MJ/km) for gasoline, diesel, LPG and HEV was derived from 60 categories of PCs. The disaggregated mileage was also aggregated into the four categories (i.e. gasoline, diesel, LPG and HEV) and adjusted by using ratios of aggregated total fuel consumption and fuel consumption derived by original mileage, population and with average fuel efficiencies.

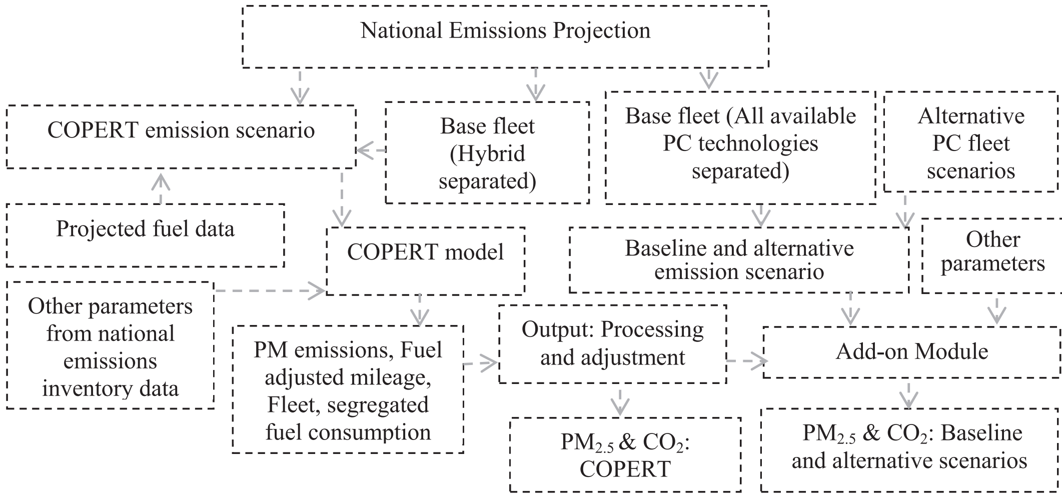

Fig. 1. Research methodology.

Exhaust PM, total $PM_{2.5}$, and total CO_2 emissions were also aggregated into these four PC categories. The exhaust PM was considered as exhaust $PM_{2.5}$ (EMEP/EEA, 2016; EMISIA, 2016), and thus, total non-exhaust $PM_{2.5}$ was separated from total $PM_{2.5}$, which was aggregated from tyre and brake wear (EMISIA, 2016). The yearly non-exhaust $PM_{2.5}$ implied emission factors (g/km) were calculated using mileage data. The distribution between tyre and brake wear were calculated based on the percentage distribution of the emission factors of brake and tyre wear from EMEP/EEA (2016). These factors for the brake and tyre wear were calculated from the emissions factor for total suspended solids (TSP) and its particle size distribution. To calculate road abrasion, the emission factor (g/km) from EMEP/EEA (2016) was applied with mileage. Implied emissions factors (g/MJ) for exhaust $PM_{2.5}$ and total CO_2 emissions were calculated using the corresponding energy consumption.

2.2.2. Mileage

To distribute total mileage among different PC categories, a weighting matrix was developed where the primary input was PC mileage per year per vehicle for gasoline, diesel, HEV and LPG from the COPERT Scenario. A similar mileage of CNG to LPG, PHEV (Gasoline) to HEV (Gasoline), HEV (Diesel) & PHEV (Diesel) to diesel and EV/FCV to gasoline, was assumed. The weightings matrix was calculated in each year as: (mileage x available fleet)/(sum of the mileage from available fleet).

2.2.3. Fuel demand and emission

Fuel demand was calculated for exhaust emissions. Fuel efficiency, fuel efficiency uplift multipliers, PC population and mileage were required for this calculation. The fuel efficiency data (km/MJ) in Table 1 was mostly obtained from COPERT for the year 2015. Fuel efficiency for alternative PC technologies were derived from Table 2. In addition, improvement in the average fuel efficiency of some PCs was calculated from Table 1.

Using Tables 1 and 2 in relation to the vehicle population and mileage data the total energy demand (MJ) was calculated using Eq. (1). The equation for fuel consumption is a product of mileage and fuel efficiency. Instead of using a constant fuel efficiency factor, fuel efficiency in future years is subject to variations for gases (e.g. CO_2) and time frame (e. g. 2015–2031) based on fuel efficiency data of 2015. Multipliers in Table 2 were used to calculate fuel efficiency in relation to the PC categories in Table 1 (e.g. efficiency of EV/FCV is 2/2.9 time better than that of diesel; HEV gasoline is 1.9 times better than a conventional gasoline PC). Finally, the total emissions were calculated using implied emission factors for exhaust $PM_{2.5}$ and CO_2.

$$F_{t,i} = \Big(P_{k,t}{*}Effi_{i,t} + P_{s,(t-1)}{*}Effi_{i,(t-1)} + P_{s,(t-2)}{*}Effi_{i,(t-2)} + \ldots + P_{s,(t-n)}{*}Effi_{i,(t-n)}\Big){*}A_{i,t} \quad (1)$$

Here, $F_{t,i}$ = Energy demand in year t for PC technology i; $P_{k,t}$ = Newly registered PC in year t; $P_{s,(t-n)}$= Estimated Survived PC population in the previous years (n = 1, 2, n); $A_{i,t}$ = Mileage for PC technology i in year t; $Effi_{i,(t-n)}$ = Fuel efficiency which was subject to the yearly efficiency improvement and also efficiency uplift for some technologies.

For non-exhaust emissions, the estimation process was a multiplication of total mileage (derived from a disaggregated fleet by a disaggregated mileage) in a category by the corresponding emission factors (Eq. (2)).

$$E_{non,i,j} = P_i{*}A_i{*}EF_{non,i,j} \quad (2)$$

Here, $E_{non,i,j}$ = Non-exhaust emission j for PC technology i, P_i = Total population for PC technology i in a year; A_i = Total mileage population for PC technology i in a year, $EF_{non,i,j}$ = emissions factor for non-exhaust emission j for PC technology i.

2.3. Fleet and scenarios

The fleet for Baseline Scenario and EV Policy Scenario were obtained from the COPERT Scenario (Alam et al., 2017a), however, all subclasses of HEV and PHEV were aggregated in this study. The EV Policy Scenario addressed the existing Electric Vehicle policy in Ireland. The Non-conventional PC Scenario represented a possible ban on the sale of conventional vehicles powered by gasoline and diesel in the future. Total mileage and the total number of PCs were the same between all emissions scenarios. Details of the scenarios were presented in the Table 3.

In EV Policy Scenario, sales for different technologies were determined by the current national policy regarding EVs. The PC technologies were considered similar to the disaggregated Baseline Scenario except for a higher proportion of EVs and PHEVs. A total of 50,000 EVs and PHEVs by 2020 were modelled in line with national policy targets. Its growth after 2020 was calculated based on a modelled growth curve ($y = 25422\ln(x) + 531$, where x = year started from 2014, and y = EV and PHEV numbers). This curve was selected (Alam et al., 2017a) as it gave an acceptable share of the EVs and PHEVs by 2035 (51% of the total sales). The split between

Table 1
Fuel efficiency data for each fuel and vehicle type.

	Diesel	Gasoline	CNG	LPG
Fuel efficiency (km/MJ) in 2015	0.4075	0.3661	0.3840[a]	0.3923
Average improvement rate 2016–2030 for CO_2	0.0%	0.0%	1.30%	1.30%
Average improvement rate 2031–2035 for CO_2	0.0%	0.0%	1.12%	1.12%
Average improvement rate 2016–2035 for $PM_{2.5}$	0.0%	0.0%	0.0%	0.0%

[a] Ou et al. (2010), Gambhir et al. (2015).

Table 2
Fuel efficiency uplift for low-carbon vehicles over conventional vehicles.

FCV	EV	HEV (Gasoline & diesel)	PHEV (Gasoline & diesel)	LPG/CNG
2[a]	2.9[a]	1.9[c]	1.9[c]	1[b]

[a] Hill et al. (2012).
[b] Gambhir et al. (2015).
[c] COPERT.

EV and PHEV in the calculation was considered, based on their share in the disaggregated Baseline Scenario. The sales for other PC technologies were assumed similar to the baseline. In this scenario, only vehicles currently available as PC technologies were considered.

For the Non-conventional PC scenario, the shares of the sales for different low carbon technologies were gradually increased. New sales of conventional PCs powered by gasoline and diesel fossil fuel were phased out by 2030. The concept followed a recent trend of proposals for banning fossil fuelled PCs, e.g. the Netherlands is proposing to ban new sales of conventional PCs by 2025 (NOS, 2016). Similarly, Norway is proposing to ban gasoline vehicles and moving to 100% green energy for PCs by 2025. In this scenario, a penetration of CNG was considered from the year 2025 as a recent policy paper on energy indicated that building of CNG filling stations would commence from 2025 (DCENR, 2016), in response to European legislation (Directive, 2014/94/EU). FCVs were also considered from the year 2030 onwards. The total cumulative sales for all new technologies between the years 2015 and 2035 were segregated according to Table 4. The share of the cumulative sales was assumed or estimated by the authors in light of the policies, and the current vehicle penetration trends (Alam et al., 2017a).

For the yearly distribution of new car sales, the above vehicle categories were aggregated based on their existing market share and future market penetration capabilities (see Table 5). These were then later disaggregated and adjusted for fleet EV Policy Scenario and Non-conventional PC Scenarios, following the same approach described in Alam et al. (2017a). The distribution was conducted following a fitted curve (Eq. (3)) and using the parameter values in Table 5. The following equation represents the conventional S-curve for a technology penetration throughout its life time, however, was modified using a multiplying factor ‘m’ (Alam et al., 2017a).

$$CFleet_y = m * \frac{C_{2015-2035}}{1 + e^{-k(y - y_{mid})}} \quad (3)$$

Here, $CFleet_y$ is the cumulative fleet distribution for the year y; $C_{2015\text{-}2035}$ is the cumulative total of new sales from 2015 to 2035 for a group; $\underline{k}$ = the steepness of the curve, in a standard S-curve $k = 1$; y_{mid} is the year when half of the total cumulative sales are expected to be distributed between initial year and y_{mid}; m is a multiplier used to raise curves which is the ratio of the actual cumulative value and cumulative value of the first iteration.

3. Results

3.1. Fleet

The fleet in the disaggregated Baseline Scenario in Fig. 2 shows all the available technologies except FCV and CNG which were not present in Ireland in 2015. In this scenario, gasoline and diesel PCs dominated the fleet having similarity to historic years (Alam et al., 2017b). The shares for gasoline and diesel PCs in total were 35% and 63% respectively in 2035 (Fig. 2a). According to the estimation in this study, 3.1 million new PC will enter the Irish market in the 2015 to 2035 period. Approximately 32% and 67% of the new sales will be entered in the Baseline Scenario as gasoline and diesel PCs (Fig. 2b). Together from the Fig. 2a and b, the replacement of gasoline PCs by the diesel counterpart is noticeable. This reflects the impact of a carbon -differentiated taxation policy initiated in 2008 (Alam et al., 2017b). Diesel PCs, specifically small engine sizes were preferred by the user due to a low tax rate (Alam et al., 2017b) which was modelled in COPERT scenario (Annex I).

Table 3
Different scenarios at a glance.

Scenarios	Fleet	Mileage	Fuel	Emission estimated at
COPERT	Existing disaggregated vehicle technologies (by engine size, emission standard, and fuel: gasoline, diesel and LPG); For HEV (only gasoline).	Mileage at EURO standard level: National estimation, or similar to the national estimation (for HEV only).	Fuel: Total Fuel (National estimation); Bio-fuel share (6.8% up to 1990 and then 12% until 2035 of the fossil fuel).	COPERT
Baseline	Existing PC technologies (aggregated at the fuel technology level).	Mileage from COPERT (with a mileage weighting matrix).	Fuel estimation made by energy consumption per mileage; Biofuel share similar to the COPERT.	Add-on Module
EV policy Scenario	PC technologies in Baseline plus Diesel HEV, EV and PHEV (Gasoline and Diesel); Fleet size according to policy for EV and PHEV	See Baseline.	See Baseline.	Add-on Module
Non-conventional PC scenario	PC technologies in EV policy Scenario, plus CNG and FCV; Defined number of technological penetration with an aim to phase out conventional gasoline and diesel fossil fuel powered PCs by 2030.	See Baseline.	See Baseline.	Add-on Module

Table 4
Penetration of different PC technologies in different Scenarios.

Assumption for 2015–2035	Baseline[a]	EV Scenario	Non-conventional PC Scenario
Gasoline	31.86%	13.09%	6.00%
Diesel	67.53%	45.80%	7.00%
EV	0.12%	39.73%	24.00%
HEV (Gasoline)	0.45%	1.00%	13.00%
HEV (Diesel)	0.00%	0.01%	18.00%
PHEV (Gasoline)	0.00%	0.14%	10.00%
PHEV (Diesel)	0.00%	0.14%	12.00%
LPG	0.04%	0.08%	5.00%
CNG	0.00%	0.00%	1.00%
FCV	0.00%	0.00%	4.00%

[a] Alam et al. (2017a).

An assumption was made of having a higher EV penetration than the current national EV policy in the EV Policy Scenario. This resulted in a share of gasoline, diesel and EV PCs at 13%, 39% and 47% respectively in 2035 (Fig. 3a). This was because of 13%, 46% and 40% penetration of new sales of gasoline, diesel and EV PCs in the projection period (Fig. 3b). In the Non-conventional PC Scenario, the penetration of new gasoline and diesel was designed to end in 2030 which resulted in a very low share (6% gasoline and 5% diesel) of conventional vehicles by 2035 (Fig. 4a). In this scenario, 6% and 7% of the 3.1 million new PC sales were distributed in 2015–2030 as gasoline and diesel respectively. The largest and the second largest shares were EV and HEV at 30% and 28% in 2035. This was the result of the penetration of 24% and 31% of new sales of EV and HEV in the period of 2015–2035 (Fig. 4b).

3.2. CO_2 emission

CO_2 emissions in the EV Policy Scenario and Non-conventional PC Scenario were much lower than the Baseline Scenario in Fig. 5. Baseline CO_2 emissions were 7186.7 kt in 2035 whereas 3417.6 kt and 2223.1 kt of CO_2 emissions were produced in 2035 under EV Policy and Non-conventional PC Scenarios. The highest level of reduction was 69% in 2035 from 2015 level in Non-conventional PC Scenario. The COPERT and baseline scenarios show the consistency between two emission modelling approaches.

3.3. Exhaust $PM_{2.5}$ & non- exhaust $PM_{2.5}$

The total $PM_{2.5}$ emissions reduced until 2028 in all scenarios and gradually increased in the rest of the projected period (see Fig. 6). The baseline scenario is consistent with the COPERT projection and the baseline $PM_{2.5}$ emission was 767.9 tonnes in 2028 and this was 33% lower than total $PM_{2.5}$ in 2015. The total reduction was 26% from 2015 to 2035, from 1144.1 tonnes in 2015 to 845.9 tonnes in 2035. The estimated total $PM_{2.5}$ emissions in EV Policy and Non-conventional PC Scenarios in 2035 were 764.18 tonnes and 718.1 tonnes respectively. The poorest $PM_{2.5}$ emissions reductions occurred in EV policy Scenario throughout the time series and the reduction was 33% by 2035. EV Policy Scenario had a higher penetration of EVs and produced higher amounts of non-exhaust tyre wear and road abrasion $PM_{2.5}$ because of their comparatively higher vehicle weight than that of conventional gasoline or diesel PCs. However, it is important to note that conservative emission factors for brake wear for EV and FCV were used which effect the EV policy scenario more than that of the Non-conventional PC scenario.

The comparison of total $PM_{2.5}$ emissions values in 2015 and 2035 in Fig. 7 showed that the most notable reduction occurred in the exhaust emissions for all the scenarios. On the other hand, non-exhaust emissions except brake wear increased from 2015 to 2035 due to an increase of overall mileage in all scenarios. Brake wear emission shows an opposite trend because of the conservative estimation of the emission factor. Both EV Policy Scenario and Non-conventional PC Scenario had lower exhaust $PM_{2.5}$ emissions in comparison to the baseline due to fuel efficiency improvements and penetration of alternative vehicles. However, Non-conventional PC Scenario had a greater reduction in exhaust $PM_{2.5}$ than that of emission EV Policy Scenario throughout the time series as a result of a lower penetration of gasoline and diesel vehicles (11% of the total sales between 2015 and 2035).

Tyre wear emissions increased the most (42%) followed by a 39% increase in road abrasion $PM_{2.5}$ emissions in 2035 in the Non-conventional PC Scenario, as a result of higher weight of vehicles in EV penetration. Non-exhaust brake wear $PM_{2.5}$ emissions from the EV Policy Scenario was lower than that of Non-conventional PC Scenario due to a higher total mileage of EVs. This was the result of higher penetration of EVs (40%) in EV Policy Scenario in comparison to Non-conventional PC Scenario (24%). Brake wear emissions from EVs and FCVs were assumed zero because of improvements in their braking systems which was consistent for both scenarios. Road abrasion emission is 1.14–1.17 times lower than that of tyre wear throughout the time series for all scenarios which reflects the difference between road abrasion and tyre wear emission factors used in the Add-on module (Annex II & III).

The ratio of total exhaust to total non-exhaust $PM_{2.5}$ in 2015 was 0.97 for both, Baseline Scenario, and EV Policy Scenario and 1.01 for Non-conventional PC Scenario (as shown in Fig. 8). However, the ratios changed to 7.5, 15.0 and 33.9 in 2035 for the Baseline, EV and

Table 5
Parameters values in the Eq. (1) for EV Policy & Non-conventional PC Scenario.

Group	Remarks	Technology	EV Policy Scenario[a]	Non-conventional PC Scenario
1	Healthy Market Share	Gasoline & Diesel	$y_{mid} = 2022$; $k = 0.1$;$m = 2.1$	$y_{mid} = 2016$; $k = 0.4$;$m = 1.4$
2	Shows a promising growth	HEV and PHEV	$y_{mid} = 2035$; $k = 0.18$;$m = 2.09$	$y_{mid} = 2015$; $k = 0.29$;$m = 1.10$
3		EV & FCV	–	$y_{mid} = 2035$; $k = 0.29$;$m = 2.1$ $y_{mid}{}^{b} = 035$;$k^{b} = 0.5$;$m^{b} = 2.14$
4	Very low market share	FCV &/CNG	$y_{mid}{}^{b} = 2035$; $k^{b} = 0.5$; $m^{b} = 2.01$ (CNG); 2.1 (FCV)	$y_{mid}{}^{b} = 2035$; $k^{b} = 0.5$;$m^{b} = 2.01$;

[a] Alam et al. (2017a).
[b] Applicable for CNG and FCV.

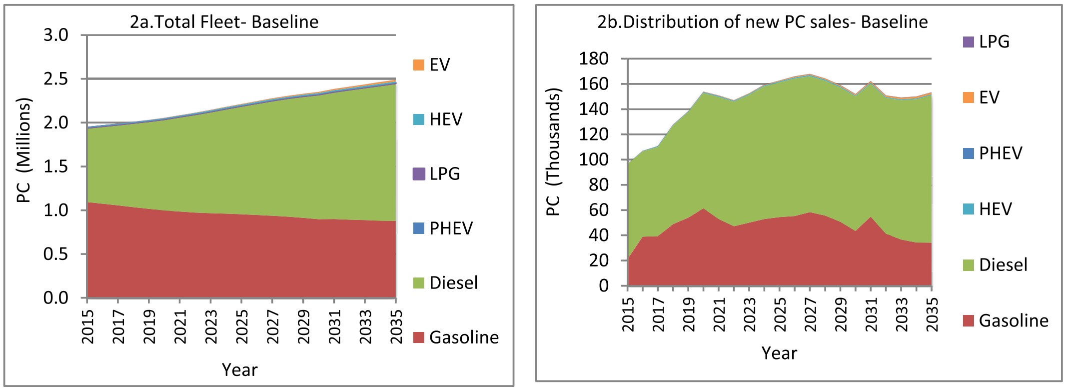

Fig. 2. Total disaggregated Baseline fleet.

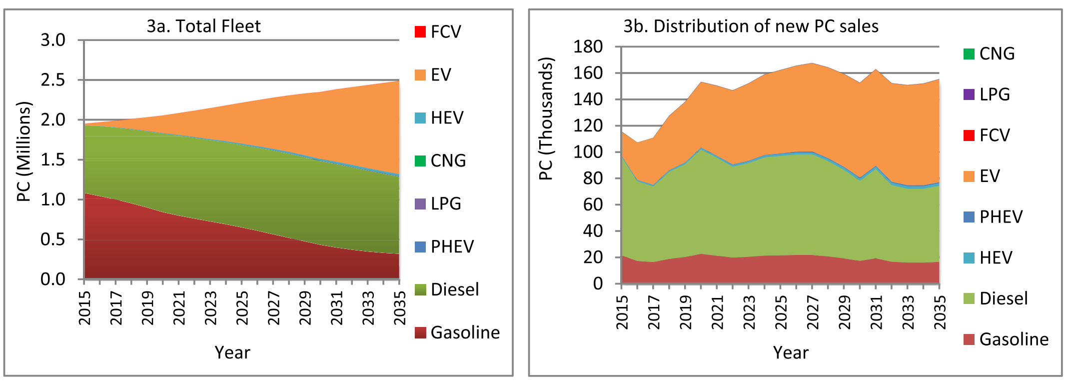

Fig. 3. Fleet in EV policy scenario.

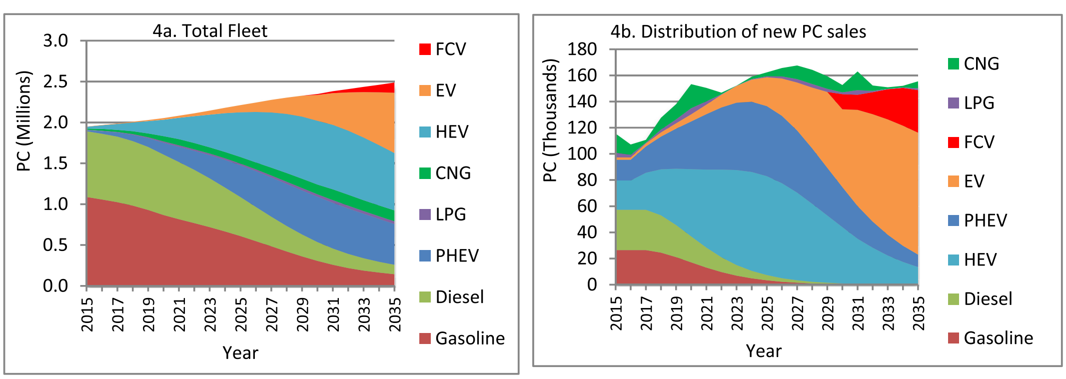

Fig. 4. Fleet in non-conventional PC scenario.

Non-conventional PC Scenarios respectively.

3.4. CO_2 emission vs. $PM_{2.5}$

CO_2 emissions reductions were 52% and 69% in the EV Policy and Non-conventional PC Scenarios respectively, in comparison to the Baseline Scenario in 2035 (see Fig. 9). In comparison, $PM_{2.5}$ emissions reduction percentages were 9% and 15% in 2035.

4. Discussion

This study provided likely future $PM_{2.5}$ scenarios under the current vehicle trends and under various policy options. In addition, this study included alternative PC technologies in these future scenarios. The Baseline Scenario resulted in a 26% reduction of $PM_{2.5}$ emissions in 2035 from the 2015 level, whereas the reduction figure for CO_2 in the same period was less than 1% despite the increase of fuel and mileage use. This reduction of exhaust $PM_{2.5}$ emission resulted from lower emission in future years with the improvement of the EURO emission standard embedded within the implied emission factor. CO_2 emission was also reduced due to EURO emission standard as well as the use of bio-fuel. However, their reduction was limited by the impact of increased mileage, as CO_2 is proportionally related to fuel consumption or mileage driven unlike $PM_{2.5}$.

Where alternative fleet technology is concerned, CO_2 emissions reduction was the highest in the Non-conventional PC Scenario (69% lower in 2035 from 2015) in comparison to $PM_{2.5}$ (36% lower in 2035 in comparison to 2015). This $PM_{2.5}$ emission trend could be slightly higher for the EV policy scenario compared to the Non-

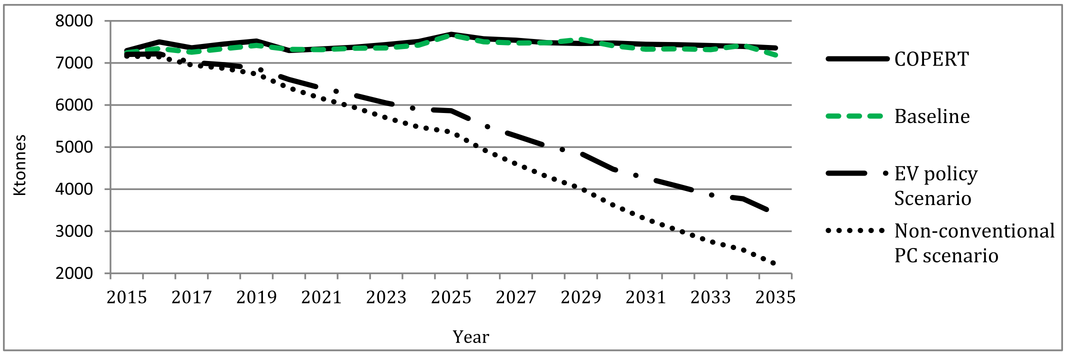

Fig. 5. Total CO_2 from all the scenarios.

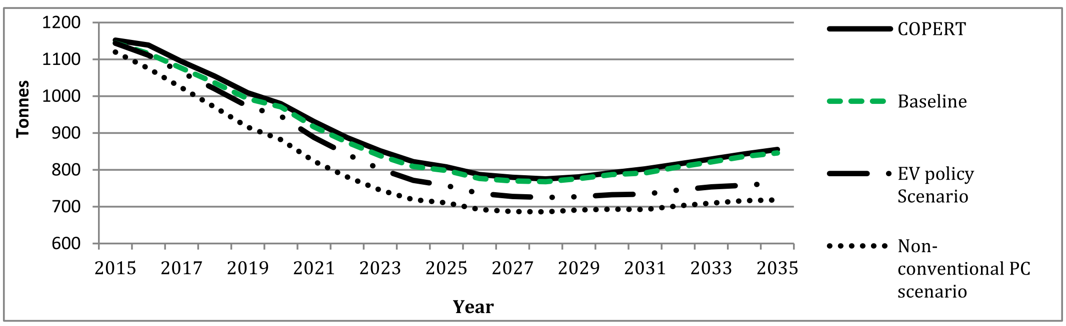

Fig. 6. Total $PM_{2.5}$ from all the scenarios.

conventional policy scenario, if alternative brake wear emission factors were used. These are reported to be very low but there is a lack of information on this emission factor in the literature in general and thus assumptions must be made in their absence (Timmers and Achten, 2016).

In addition, total $PM_{2.5}$ trends showed an upward tendency after 2028 which is similar to a finding in a recent UK study by Lott et al. (2017), while total CO_2 emissions continuously went down. However, this study showed a different finding than that of Dhar et al. (2017) in India who showed that the $PM_{2.5}$ reduction was more than 60% from a reference scenario in 2050 whereas CO_2 reduction was nearly 38%. The contribution of this $PM_{2.5}$ reduction may be associated with a shift to two wheels and a PC composition, however, a detailed disaggregation of the $PM_{2.5}$ emission may be required to accurately model this future scenario. In the current study our methodology, separates the contributions of three non-exhaust emissions which are modelled separately. This was not considered in many previous studies (Dhar et al., 2017; Lott et al., 2017; Pathak and Shukla, 2016; Xia et al., 2015). Furthermore, a number of detailed vehicle classes were also considered in our methodology which were not explicitly considered in the international arena including the above studies. In order to consider this level of disaggregation, emission factors for a number of PC technologies were derived from sources based on the literature and implied emission factors in Ireland. This work highlights a gap in the literature for $PM_{2.5}$ emission factors for a range of modern and future PCs such as EV, PHEV, and FCV. The model structure is also flexible to adopt to future improvements in the emission factors when available, and thus becomes a useful framework for the emission modelling.

A comparison between the emission reduction potential in different scenarios highlights that co-benefits can be achieved for both air pollutant (i.e. $PM_{2.5}$) and GHG emissions (i.e. CO_2). However, the level of the benefit is restricted to some extent for particulate air pollutants due to the non-exhaust component, and these resulted in an upward emissions trend. This is because of the nature of the emission sources where air pollutants are associated with both fuel and mileage, unlike GHGs, which is dependent on

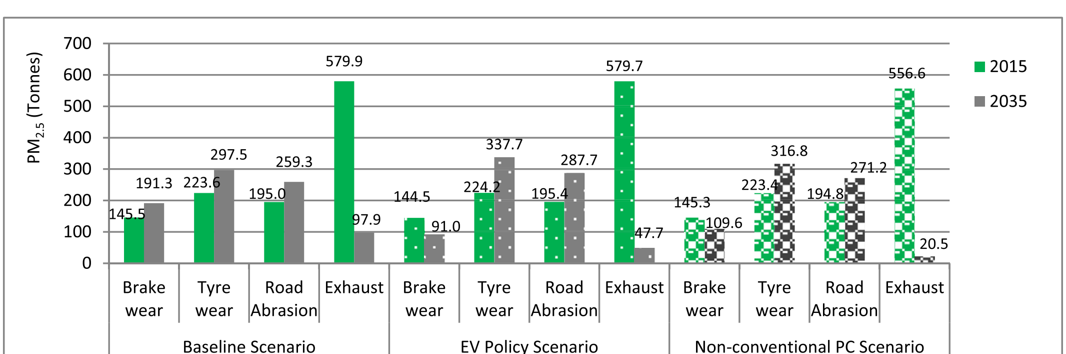

Fig. 7. Breakdown of $PM_{2.5}$ emissions.

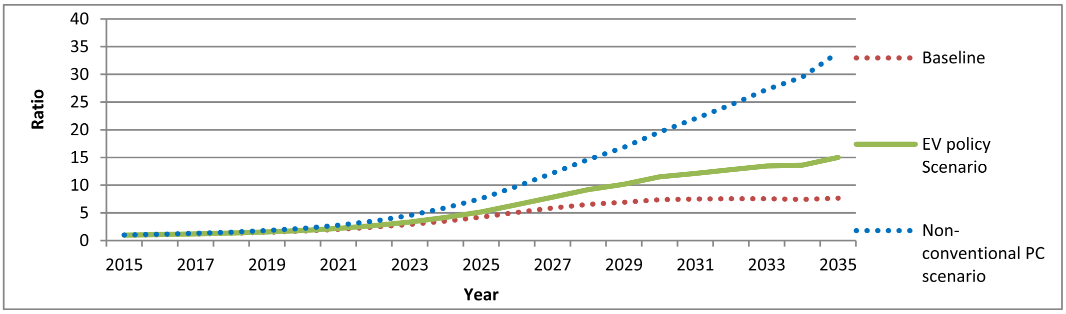

Fig. 8. Non-Exhaust to Exhaust ratio.

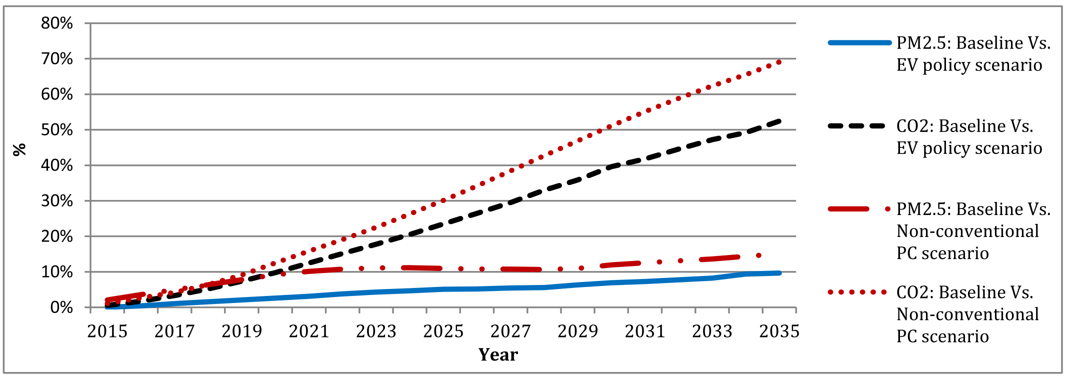

Fig. 9. Emissions reduction all the scenarios (CO_2 vs $PM_{2.5}$).

fuel consumption. While considering health effects near roads, the increase in mileage also contributes to the re-suspension of $PM_{2.5}$ regenerated by turbulence and tyre wear of the vehicle from road dust. Along with road transport, the source of the road dust includes nearby vegetation, corrosion of street furniture and human activities such as industry. The resuspension of $PM_{2.5}$ is almost two times higher than combined exhaust and non-exhaust $PM_{2.5}$ for EVs and is similar to conventional vehicles on a kilometre basis according to Timmers and Achten (2016).

This study highlights that national emissions inventories using the COPERT methodology do not accurately capture future technologies and importantly may not fully account for the impact of non-exhaust emissions in their assessments of environmental impacts and policy. As is clearly shown here, the expected increasing demand for travel (i.e. mileage) in future and the comparatively higher weight of EVs, results in significantly more $PM_{2.5}$ non-exhaust emissions. This study also highlights that a policy which heavily incentivises the use of alternative fuels and technology will result in significant CO_2 savings but may not result in significant particulate matter reductions. Thus the importance of the integration of air pollution and climate change policy, as highlighted by many authors recently, is shown to be very important in this context (Bollen and Brink, 2014). In the coming years, fuel consumption related emissions will likely be reduced gradually with the increase of tighter emissions control for regulated gases/pollutants. Non-regulated exhaust pollutants will also decrease in the process due to increased fuel efficiency. However, non-exhaust emissions must also be reduced to improve air quality. In order to do that, travel demand for PCs (in terms of mileage) must be replaced with sustainable and smarter travel options such as walking and cycling. In the long term, non-exhaust $PM_{2.5}$ will become a larger threat to health and will adversely affect the success of governmental efforts. In addition, the improvement in the emissions estimation methodology proposed here, will also help various countries in the preparation of $PM_{2.5}$ emission inventories under the Gothenburg protocol and NEC directive. Overall, this methodology and add-on module can be readily adopted to any other gases and pollutants by changing the implied emissions factors which are available in COPERT and the literature.

5. Conclusion

Road transportation is one of the largest contributors to CO_2 and $PM_{2.5}$ emissions in Ireland. The modelling process in this study provided indicative future scenarios at a detailed level to inform emission reduction policies. While air quality policies are often focused on a reduction of $PM_{2.5}$ concentration, and climate changes policies on GHG emissions reduction, this research highlights that a focus must also be paid on the quantitative reduction of $PM_{2.5}$ at the sources. In particular, the non-exhaust component of $PM_{2.5}$ needs to be considered in integrated air pollution and climate change policy. While low carbon fuel technologies in the road transport sector may offer large benefits in reducing GHGs, their impact on air pollution from their non-exhaust emission should not be ignored. Thus, integrated air pollution and climate change policies must focus on restraining travel demand in passenger cars. Moriarty and Honnery (2013) highlighted that for a deep transport emission (e.g. CO_2) cut in existing economies, a change in transport policy that reduces passenger travel levels will be the most effective solution. In addition, a focus should be paid on an improvement in tyre and road material and technologies for the reduction of $PM_{2.5}$ emissions. Without such measures, $PM_{2.5}$ is likely to remain a persistent pollutant in many countries for the foreseeable future.

This study also shows that at the current state of the technology penetration and even with higher levels of biofuels, CO_2 and $PM_{2.5}$ emission will not reduce significantly in Ireland. Higher levels of technological intervention might contribute a lower level of emissions in future years. Banning of non-conventional vehicles shows a

better future than the EV policy scenario for both CO_2 and $PM_{2.5}$ emissions. A policy addressing both might deliver further benefits in the regime of integrated air pollution and climate change policy.

The modelling process developed in this study has some limitation, especially regarding $PM_{2.5}$ exhaust emission factors. Further research in this area is required for quantifying the contribution of exhaust $PM_{2.5}$ for different technologies, e.g. PHEV and their subclasses e.g. mild and full PHEV. The add-on module, however, has a provision to accept the future emission factors to improve quantification. With the current level of knowledge in this area, the modelling process enables modellers to develop scenarios for a range of fuel technologies.

Acknowledgements

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ANNEX I

Annex I represents the EURO classification PC applied in COPERT model.

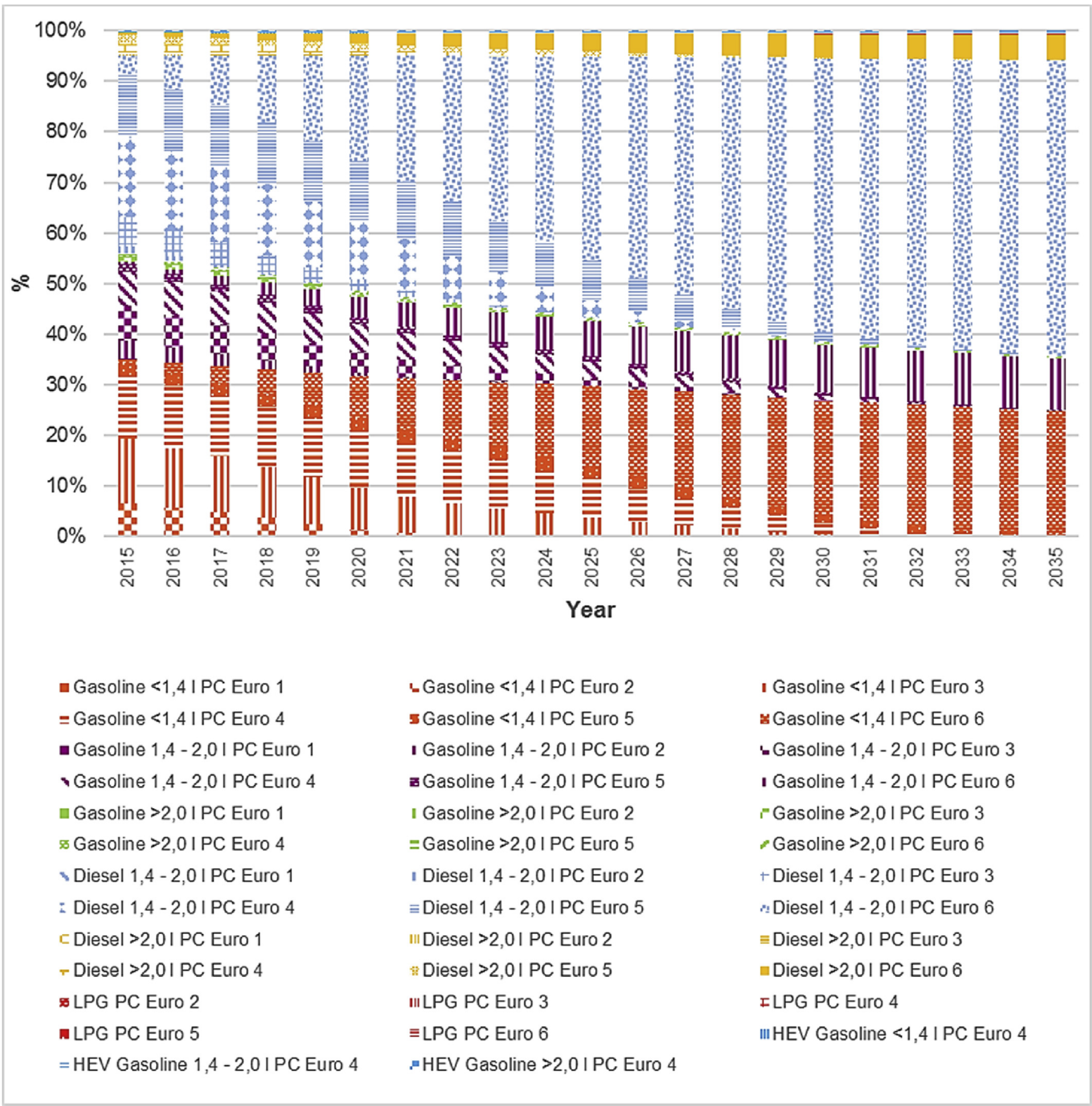

Fig. I. Share of EURO emission technologies (EURO 1 to Euro 6) between different fuel and engine sizes (Gasoline: <1.4L, 1.4–2L, >2L; Diesel: <2L & >2L; HEV 1.4–2L & >2L; LPG: no segregated data on engine size).

ANNEX II

Annex II represents the implied emission factors in three tables and reference emission factors for verification.

Table I
Non-Exhaust $PM_{2.5}$ (g/km).

Year	COPERT (2015–2035)				NAEI (2013)
	Gasoline Mild HEV	Diesel	Gasoline	LPG	Passenger car
Brake	0.0031	0.0034–0.0035	0.0034–0.0036	0.0031	0.003
Tyre	0.0047	0.0052–0.0054	0.0052–0.0055	0.0047	0.005
Road Surface[a]	0.0041	0.0046–0.0047	0.0046–0.0048	0.0041	0.004

[a] Emission factor applied from EMEP/EEA (2016) on COPERT mileage.

Table II
Exhaust $PM_{2.5}$.

Year	Diesel		Gasoline	
	g/MJ	(g/km)	g/MJ	(g/km)
2015	0.0098	0.024	0.0005	0.001
2016	0.0089	0.024	0.0005	0.001
2017	0.0080	0.024	0.0005	0.001
2018	0.0071	0.024	0.0005	0.001
2019	0.0062	0.024	0.0005	0.001
2020	0.0053	0.024	0.0005	0.001
2021	0.0045	0.024	0.0005	0.001
2022	0.0037	0.024	0.0005	0.001
2023	0.0030	0.024	0.0005	0.001
2024	0.0024	0.024	0.0005	0.001
2025	0.0019	0.024	0.0005	0.001
2026	0.0015	0.024	0.0005	0.001
2027	0.0012	0.024	0.0005	0.001
2028	0.0010	0.024	0.0005	0.001
2029	0.0009	0.024	0.0005	0.001
2030	0.0009	0.024	0.0006	0.001
2031	0.0008	0.024	0.0006	0.001
2032	0.0008	0.024	0.0006	0.001
2033	0.0008	0.024	0.0006	0.001
2034	0.0008	0.024	0.0006	0.001
2035	0.0008	0.024	0.0006	0.001
Average		0.008		0.001
NAEI (2013)		0.019		0.001

Table III
CO_2 (g/MJ).

Year	Diesel	Gasoline
IPCC (2006) [a]	72.60–74.80	67.50–73.0
COPERT (2015–2035)[b]	68.50–54.70	64.63–47.93

[a] Without bio-fuel (upper and lower range).
[b] gradual decrease from 2015 as an effect of bio-fuel (lower biofuel in 2013).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.169.

References

Alam S, Duffy P, Hyde B & McNabola A. (2015). Common air pollutant projections from the Irish road transport sector under the emissions celling directive (NECD) and convention on long-range trans boundary air pollution (CLRTAP): a preliminary analysis for 2035, Environ 2015 Conference, Sligo, Ireland.
Alam, S., Hyde, B., Duffy, P., McNabola, A., 2017a. Assessment of pathways to reduce CO2 emissions from passenger car fleets: case study in Ireland. Appl. Energy 189, 283–300.
Alam, S., Duffy, P., Hyde, B., McNabola, A., 2017b. Improvement in the estimation and back-extrapolation of CO_2 emissions from the Irish road transport sector using a bottom-up data modelling approach. Transp. Res. Part D Transp. Environ. 56, 18–32.
Barlow, T., 2014. Briefing Paper on Non-exhaust Particulate Emissions from Road Transport, first ed. Transport Research Laboratory, Wokingham, UK. Available from:http://www.lowemissionstrategies.org/downloads/Jan15/Non_Exhaust_Particles11.pdf. . (Accessed 15 September 2017).
Bollen, J., Brink, C., 2014. Air pollution policy in Europe: quantifying the interaction with greenhouse gases and climate change policies. Energy Econ. 46, 202–215.
Ciborowski, P., Eyoh, I., Seltz, J., Wu, C.Y., 2007. Air Emissions Impacts of Plug-in Hybrid Vehicles in Minnesota's Passenger Fleet (Coordinator: Claflin, A.). Minnesota Pollution Control Agency.
DCENR, 2014. National Energy Efficiency Action Plan 2014.
DCENR, 2016. Biofuels, 2015. Available at: http://www.dcenr.gov.ie/energy/en-ie/Renewable-Energy/Pages/Biofuels.aspx. . (Accessed 16 March 2016).
Dhar, S., Pathak, M., Shukla, P.R., 2017. Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment. J. Clean. Prod. 146, 139–148.
Duffy, P., Hanley, E., Black, K., O'Brien, P., Hyde, B., Alam, M.S., 2015. National Inventory Submissions 2015. UNFCCC, Ireland.
EEA, 2016. Explaining Road Transport Emissions: a Non-technical Guide, 2016, Copenhagen.
EMEP/EEA, 2016. EMEP/EEA Air Pollutant Emission Inventory Guidebook – 2016.
EMISIA. (2016). COPERT 5 Training Workshop, Copenhagen, Denmark, 16th-18th October, 2016.
EPA, 2016. Personal Communication, 15th September, 2017.
Gambhir, A., Tse, K.C.L., Tong, D., Martinez-Botas, R., 2015. Reducing China's road transport sector CO2 emissions to 2050:Technologies, costs and decomposition analysis. Appl. Energy 157, 905–917.
Hao, H., Liu, Z., Zhao, F., Li, W., Hang, W., 2015. Scenario analysis of energy consumption and greenhouse gas emissions from China's passenger vehicles. Energy 91, 151–159.
Hesterberg, T.W., Long, C.M., Bunn, W.B., Sax, S.N., Lapin, C.A., Valberg, P.A., 2009. Non-cancer health effects of diesel exhaust: a critical assessment of recent human and animal toxicological literature. Crit. Rev. Toxicol. 39 (3), 195–227.
Hill, N., Varma, A., Harries, J., Norris, J., Kay, D., 2012. A Review of the Efficiency and Cost Assumptions for Road Transport Vehicles to 2050. AEA Technology plc. Report: ED 57444-Issue Number 2.
IARC, 1989. Monographs on the evaluation of carcinogenic risk to humans. In: Diesel and Gasoline Engine Exhausts and Some Nitroarenes, vol. 46. International Agency for Research on Cancer, World Health Organization, Lyon, France, pp. 41–185.
IEA, 2009. Transport, Energy and CO2,: Moving towards Sustainability. International Energy Agency.
IGES, 2010. Mainstreaming Transport Co-benefits Approach: a Guide to Evaluating Transport Projects. Institute of Global Environmental Studies.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
Kiesewetter, G., Schoepp, W., Chris Heyes, C., Amann, M., 2015. Modelling PM2.5 impact indicators in Europe: health effects and legal compliance. Environ. Model. Softw. 74 (2015), 201–211.
Krivosbto, I.N., Richards, J.R., Albertson, T.E., Derlet, R.W., 2008. The toxicity of diesel exhaust: implications for primary care. J. Am. Board Fam. Med. 21, 55–62.
Lee, M., Chen, M., Lung, S., Tsai, C., Yin, X., Mao, I., 2010. Exposure assessment of PM2.5 and urinary 8-OHdG for diesel exhaust emission inspector. Sci. Total Environ. 408, 505–510.
Lott, M.C., Pye, S., Paul, E., Dodds, P., 2017. Quantifying the co-impacts of energy sector decarbonisation on outdoor air pollution in the United Kingdom. Energy Policy 101, 42–51.
Moriarty, P., Honnery, D., 2013. Greening passenger transport: a review. J. Clean. Prod. 54, 14–22.
NAEI, 2013. Fleet Weighted Road Transport Emission Factor 2013. Available at: http://naei.beis.gov.uk/data/ef-transport. . (Accessed 14 September 2017).
NOS, 2016. Tweede Kamer: Vanaf 2025 Alleen Nog Duurzame Auto's (News on 29-03-2016). http://nos.nl/artikel/2095952-tweede-kamer-vanaf-2025-alleen-nog-duurzame-auto-s.html. (Accessed 7 January 2017).
Oberdorster, G., 2000. Pulmonary effects of inhaled ultrafine particles. Int. Arch.

Occup. Environ. Health 74, 1–8.
Oberdörster, G., Finkelstein, J.N., Johnston, C., Gelein, R., Cox, C., Baggs, R., Elder, A.C.P., 2000. Acute Pulmonary Effects of Ultrafine Particles in Rats and Mice. HEI Research Report 96. Health Effects Institute.
O'Dwyer, M., 2016. Air Quality in Ireland 2015: Key Indicators of Ambient Air Quality. Environmental Protection Agency.
Ou, X., Zhang, X., Chang, S., 2010. Scenario analysis on alternative fuel/vehicle for China's future road transport: life-cycle energy demand and GHG emissions. Energy Policy 38, 3943–3956.
Pathak, M., Shukla, P.R., 2016. Co-benefits of low carbon passenger transport actions in Indian cities: case study of Ahmedabad. Transp. Res. Part D 44, 303–316.
Pope, C.A., 2000. Review: epidemiological basis for particulate air pollution health standards. Aerosol. Sci. Technol. 32, 4–14.
Raes, F., 2009. New directions: Climate change and air pollution abatement: a bumpy road. Atmos. Environ. 43, 5132.
Timmers, V.R.J.H., Achten, P.A.J., 2016. Non-exhaust PM emissions from electric vehicles. Atmos. Environ. 134, 10–17.
Vanhulsel, M., Degraeuwe, B., Beckx, C., Vankerkom, J., De Vlieger, I., 2014. Road transportation emission inventories and projections –Case study of Belgium: methodology and pitfalls. Transp. Res. Part D 27, 41–45.
WHO, 2013. Review of Evidence on Health Aspects of Air Pollution – REVIHAAP" First Results. WHO Regional Office for Europe, Copenhagen, Denmark.
Xia, T., Nitschke, M., Zhang, Y., Shah, P., Crabb, S., Hansen, A., 2015. Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia. Environ. Int. 74, 281–290.
Zhang, H., Chen, W., Huang, W., 2016. TIMES modelling of transport sector in China and USA: comparisons from a decarbonization perspective. Appl. Energy 162, 1505–1514.